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Deep-water Noise Created by the Flight of a Vandal Missile Over a Slightly Wavy Ocean Surface

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14. ABSTRACT
A Vandal sea-skimming missile was launched from the Pacific Missile Range Facility (PMRF) on 19 March 2004. The trajectory was recorded, and sound measurements were made at seven different hydrophones located at large depths beneath the ocean surface. The hydrophones were not calibrated, and thus the recordings contain no quantitative amplitude information. In this report, a calculation is made of the predicted noise amplitude at one of the hydrophones. The calculation utilized the computer code developed by H. K. Cheng and C. J. Lee for predicting underwater noise due to a sonic boom running over a wavy ocean surface. The calculation does not agree with the test data. However, the hydrophone data appears to be corrupted with noise from sources which are unrelated to the Vandal's flight. The hydrophones are also positioned too far off the Vandal's flight track to be of use in testing Cheng and Lee's theory. Further use of PMRF is not recommended without additional instrumentation.

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Contents

Figures

Tables

1 Introduction

A Vandal sea-skimming missile was launched from the Pacific Missile Range Facility (PMRF) on March 19, 2004. The trajectory was recorded, and sound measurements were made at seven different hydrophone locations.

The hydrophones were not calibrated, and thus the recordings contain no quantitative amplitude information.

The purpose of this report is to compute a predicted noise amplitude at one of the hydrophone locations, using the code described in Ref. 1, and to compare the prediction with actual data from that hydrophone.

It is concluded that the data from PMRF are not useful to test the theory described in Ref.1. This is because the hydrophones are uncalibrated, contaminated by undefined noise sources, and positioned too far off the flight track.

2 Hydrophone Locations and Vandal Trajectory

The ground track of the Vandal trajectory, together with the horizontal locations of the hydrophones are shown in Figure 1. In the figure, the y-axis runs positive north from the launch site, and the x-axis runs positive east from the launch site.

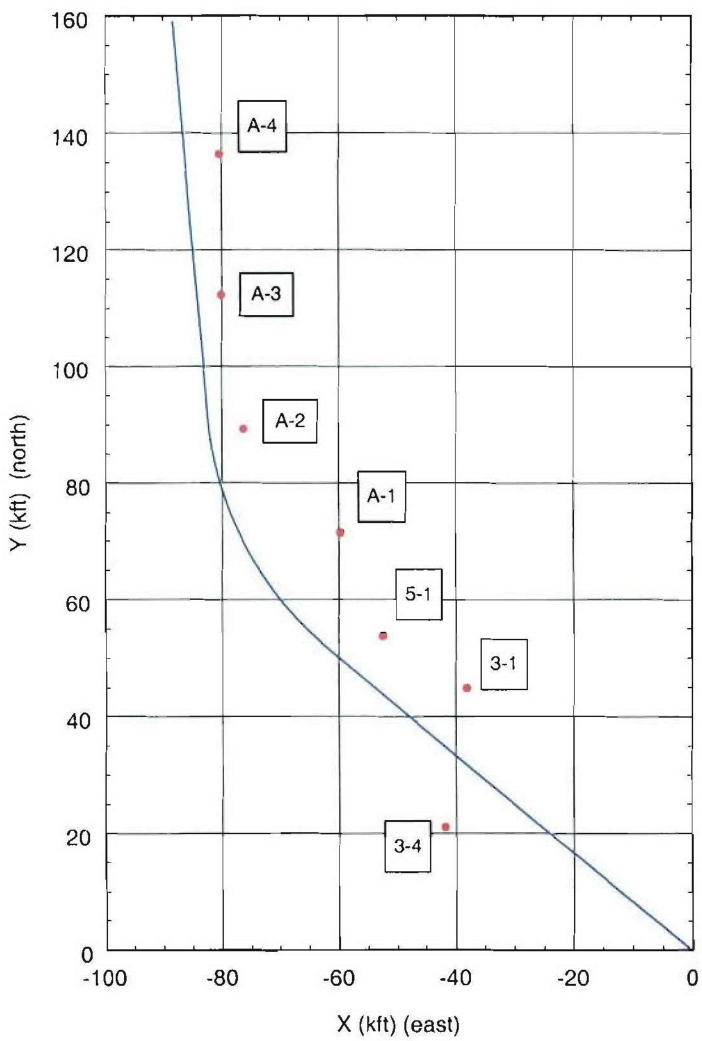

Figure 1. Vandal ground track and hydrophone locations at PMRF

In this report, azimuths will be taken counter-clockwise from the positive x-axis (east.) For the Vandal launch, PMRF weather personnel reported winds out of the north (340° geographic), which translates to 110° using our convention. The direction of propagation of the water waves (celerity vector) on the ocean surface will be assumed to coincide with the wind direction.

The locations of all seven hydrophones are given in the following table, but this report will deal with only the first one, referred to as 3-1.

Table 1. Hydrophone locations in range coordinates

Hydrophone	no.	X (kft)	Y (kft)	Z (kft)
3-1	1	-37.8172	44.8591	-2.526
3-4	2	-41.5487	21.0944	-2.7405
5-1	3	-52.1667	53.7936	-5.0340
A-1	4	-59.4375	71.4778	-8.1216
A-2	5	-76.0875	89.3458	-13.040
A-3	6	-79.8776	112.372	-14.761
A-4	7	-80.1297	136.425	-14.874

The closest approach of the Vandal ground track to each hydrophone was computed, along with the flight azimuth at the instant of closest approach. The results are given in Table 2.

Table 2. Cross-track distance and flight azimuth at closest approach

Hydrophone	no.	cross-track, y_C (kft)	azimuth (deg)
3-1	1	-10.05825	140.047
3-4	2	10.54579	140.047
5-1	3	-7.677479	140.047
A-1	4	-15.14535	125.784
A-2	5	5.845277	98.3396
A-3	6	4.136799	95.4054
A-4	7	5.990370	94.9028

The cross-track distance at closest approach is assigned a negative value if the hydrophone is on the same side of the track as the approaching wind (and water waves); otherwise, it is assigned a positive value.

The angle between the celerity vector and the vehicle's instantaneous flight azimuth is denoted by Ψ (see Ref. 1) and is always taken as positive. The angle Λ, i.e., the swept angle of the impact point (see Ref. 1), is computed as follows.

$$\Lambda = \tan^{-1}\left(\sin\phi / \tan\mu\right)$$

where the Mach angle is given by

$$\mu = \sin^{-1}\left(1/M_A\right)$$

where M_A is the flight Mach number in air (2.2163 in this case), and the ray angle to the hydrophone's surface coordinates at closest approach is given by

$$\phi = \tan^{-1}\left(y_C / h \right)$$

where y_C is the cross-track distance (given for each hydrophone in Table 2) and h is the flight altitude (0.02 kft in this case.)

For the Vandal flight at PMRF, the angles are given in Table 3 below.

Table 3. Non-alignment angle and swept angle at impact point

Hydrophone	**no.**	Ψ (deg)	Λ (deg)
3-1	1	30.047	-63.17925
3-4	2	30.047	63.17926
5-1	3	30.047	-63.17922
A-1	4	15.78410	-63.17928
A-2	5	11.66035	63.17916
A-3	6	14.59460	63.17903
A-4	7	15.09720	63.17917

The large values of swept angle are indicative of the fact that the hydrophones are positioned at distances far from the flight track in comparison to the flight altitude.

3 Water wave parameters

The theory implemented in the H. K. Cheng code (Ref. 1) yields a prediction of the noise time-history at a given underwater location for a given surface pressure disturbance, and specified wave parameters for the water surface waves.

As stated previously, the water wave direction (celerity vector) is assumed to come from an azimuth of 110°. The wave half-height (denoted by A_0 in Ref. 1) was reported to be 3 feet (Ref. 2.) The wavelength was not available from direct measurement. However the wave period was reported to be 12 sec (Ref. 2.) For this wave period, the dispersion relation for deep water waves ($\lambda = gT^2 / 2\pi$) would imply a corresponding wavelength of 737 feet. If this is the case, the slope parameter is accordingly quite small. (The waves are almost 250 times longer than they are high.)

$$\delta = A_0 / \lambda = 3/737 = 0.004$$

This very small slope parameter contrasts with the laboratory experiments described in Ref. 3, where the slope parameter ranged from 0.02 to 0.04 (five to ten times larger than for the Vandal flight.)

4 Input waveform

The waveform of the pressure disturbance created by the Vandal was computed by J.C.T. Wang (Ref. 4.) The plot below shows the waveform at the ocean surface, directly below the flight vehicle. The signature length has been normalized to unity, as has the overpressure amplitude. The physical length of the signature is 50.117 ft, and the maximum overpressure is 2.9194 psi (420.3936 psf.)

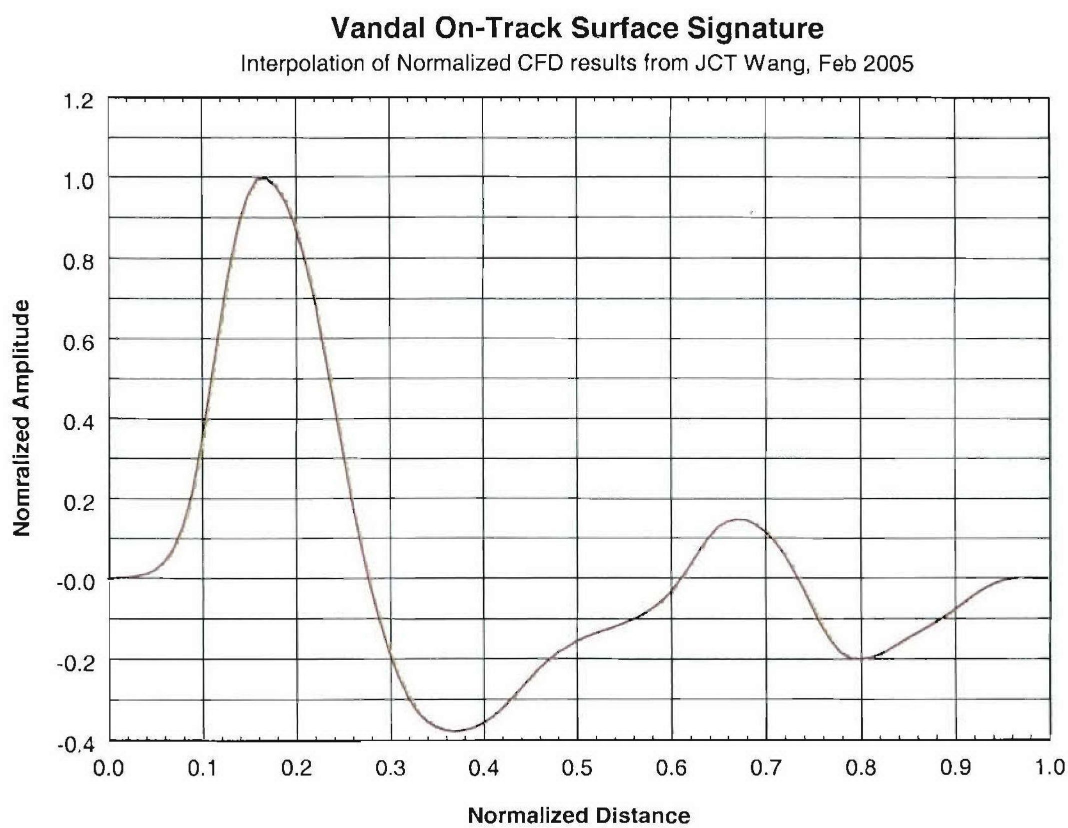

Figure 2. Vandal on-track surface signature from CFD

5 Underwater noise prediction at hydrophone 3-1

The code described in Ref. 1 was used to predict the underwater noise, due to the Vandal overflight, at hydrophone 3-1.

The input surface waveform is shown in Figure 2. The ambient sound speed in air was assumed to be 1128 ft/sec. The Vandal flight speed was 2500 ft/sec. Accordingly, the flight Mach number was

$$M_A = 2.2163$$

As stated in the previous section, the CFD results (Ref. 4) gave the following values of signature length and maximum overpressure at the ocean surface.

$$L = 50.117 \text{ ft} \qquad P_{\max} = 420.3936 \text{ psf}$$

The dimensionless depth of hydrophone 3-1 is deduced from its physical depth as:

$$z = \bar{z} / L = 2526 / 50.117 = 50.402$$

The dimensionless wave number for the water waves ($\lambda = 737$ ft) is:

$$k = 2\pi L / \lambda = 0.4272651$$

The slope parameter for the water waves, as discussed in section 3, is:

$$\delta = A_0 / \lambda = 4.07 \text{ x } 10^{-3}$$

From Table 3, the non-alignment angle and swept angle for this case are:

$$\Psi = 30.047\,^{\circ} \qquad \Lambda = -63.17925\,^{\circ}$$

As stated in section 3, the slope parameter, δ, in the laboratory experiments (Ref. 3) was five to ten times larger than for this flight situation. As well, the dimensionless wave number, k, had a value of 12 in the experiments (compared to 0.43 for the Vandal flight.)

The overpressure time-history at hydrophone 3-1 predicted by H. K. Cheng's code is shown in Figure 3.

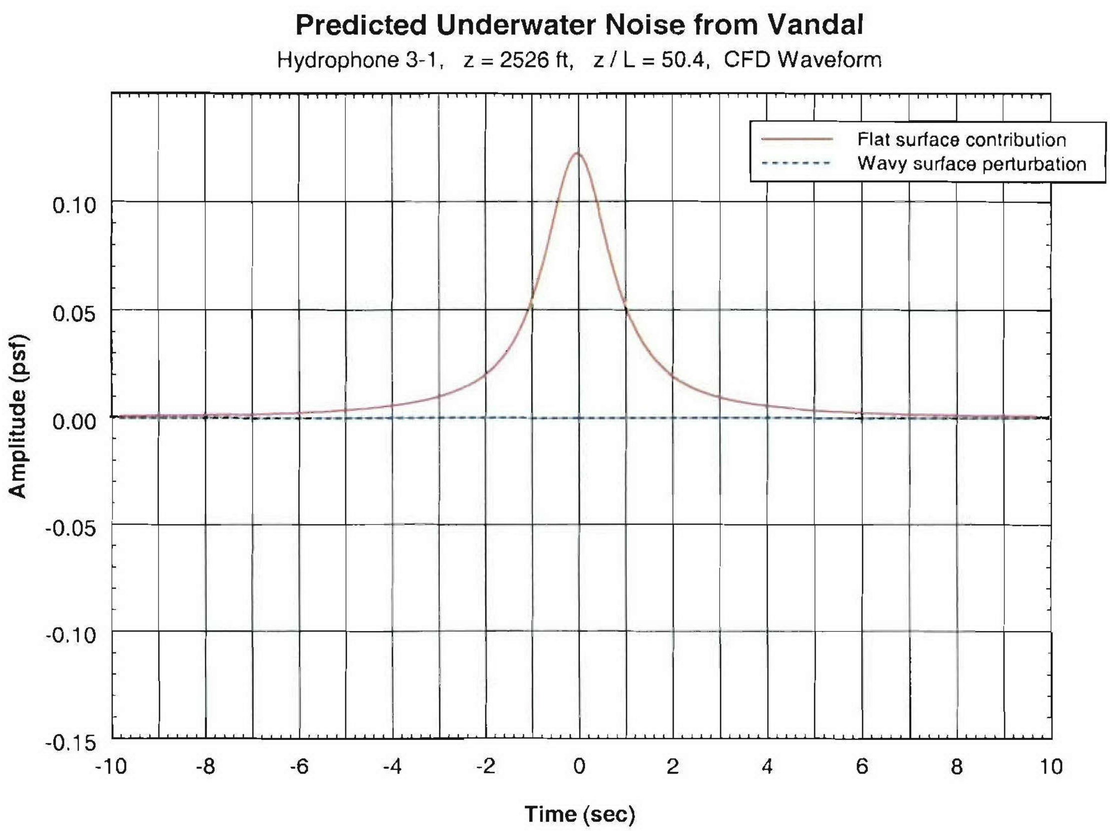

Figure 3. Predicted underwater noise from Vandal flight at hydrophone 3-1

Figure 3 shows a maximum predicted amplitude of 0.12 psf. The maximum value of the wavy surface perturbation (shown by the dashed line in Figure 3) is only 8×10^{-7} psf. The absence of influence from the wavy surface in this case may be explained with the aid of Figure 3 in Ref. 5. The values of the angles, Ψ and Λ, and the normal component of underwater Mach number, M_n, are such that the underwater receiver location is in the "horizontally propagating" domain.

6 Measured underwater noise at hydrophone 3-1

The following plot shows the signal from hydrophone 3-1, recorded at PMRF on March 19, 2004, during the actual flight of the Vandal.

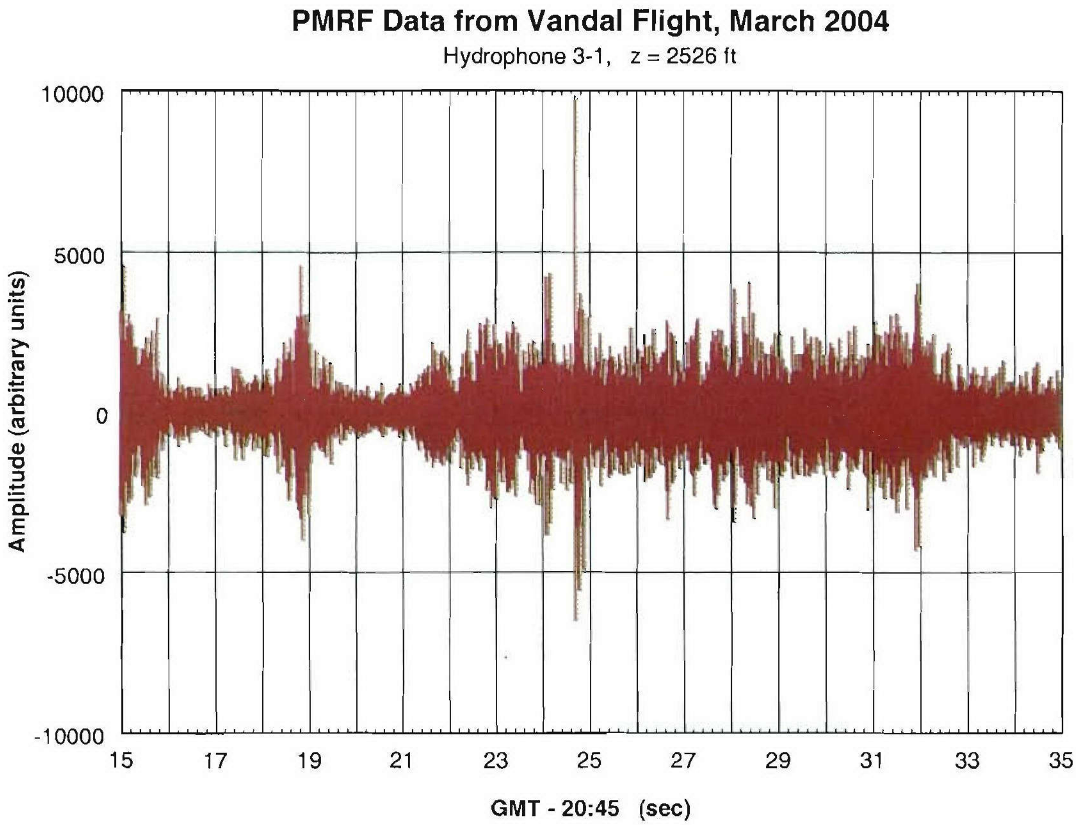

Figure 4. Measured underwater noise from Vandal flight at hydrophone 3-1

The time axis is in seconds past 20:45 GMT on that date. The maximum amplitude near 25 seconds has previously been assumed to coincide with the arrival of noise from the overflight of the Vandal. Thus, the data window from 15 to 35 seconds shown in Figure 4 should correspond to the 20-second window for the predicted signal (Figure 3.) The ordinate cannot be converted to overpressure since the hydrophones were not calibrated. Nonetheless, it is clear that the predicted pressure disturbance (Figure 3) due to the overflight does not compare well with the actual data. It is not clear whether the brief spike near 25 seconds is associated in any way with noise from the Vandal. It may simply be an indication of electrical noise in the measurement.

7 Why is the predicted noise signal positive only?

Note that the predicted signal at hydrophone 3-1 (see Figure 3) contains a positive phase only, i.e., no under-pressure.

The purely positive signal is not characteristic of the usual balanced N-wave solution. The reason we get, in this case, a purely positive signal at large depth can be traced to the nature of the CFD-generated surface waveform. The CFD waveform (see Figure 2) is unbalanced; i.e., the positive area out-weighs the negative area. This leads to a source term, i.e., a monopole term, which is not present in an N-wave (or other area-balanced waveform.) To demonstrate this effect, the prediction for hydrophone 3-1 was re-run, using a "synthetic" waveform, defined as follows.

$$p(x) = \begin{cases} \sin^2(2\pi x) & \text{for} \quad 0 \le x \le 0.25 \\ \sin(2\pi x) & \text{for} \quad 0.25 < x < 0.75 \\ -\sin^2(2\pi x) & \text{for} \quad 0.75 \le x \le 1 \end{cases}$$

The following plot shows a comparison of these two surface waveforms.

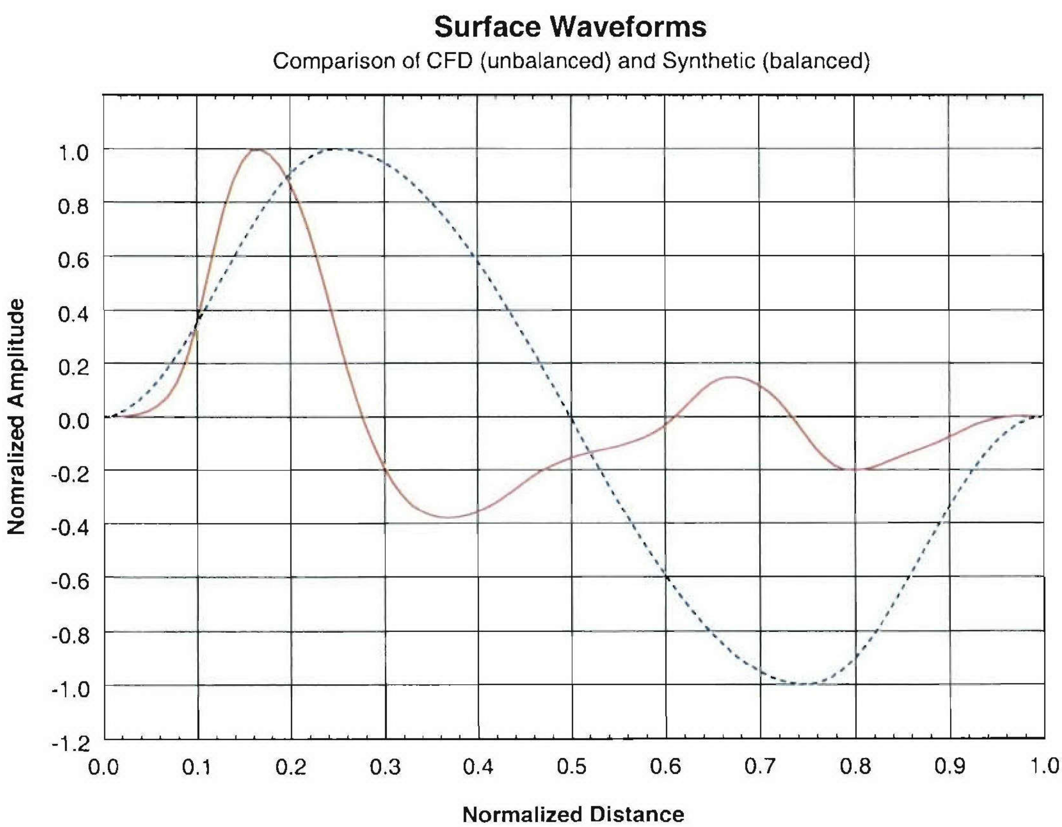

Figure 5. Comparison of CFD-generated surface waveform to a synthetic, area-balanced waveform

The synthetic waveform is area-balanced (zero first moment), but clearly has a larger second moment than the CFD waveform. (The second moment is proportional to the total energy flux generated by the wave pulse.) The following table compares the first and second moments of these waveforms.

$$M_1 = \int p dx \quad \text{and} \quad M_2 = \int p^2 dx$$

Table 4. Moments of input waveforms

Waveform	M_1	M_2
CFD	0.04	0.12
Synthetic	0.00	0.44

The following plot shows the results from running the H. K. Cheng code (Ref. 1) with exactly the same inputs as before, but with the CFD waveform replaced by the synthetic waveform.

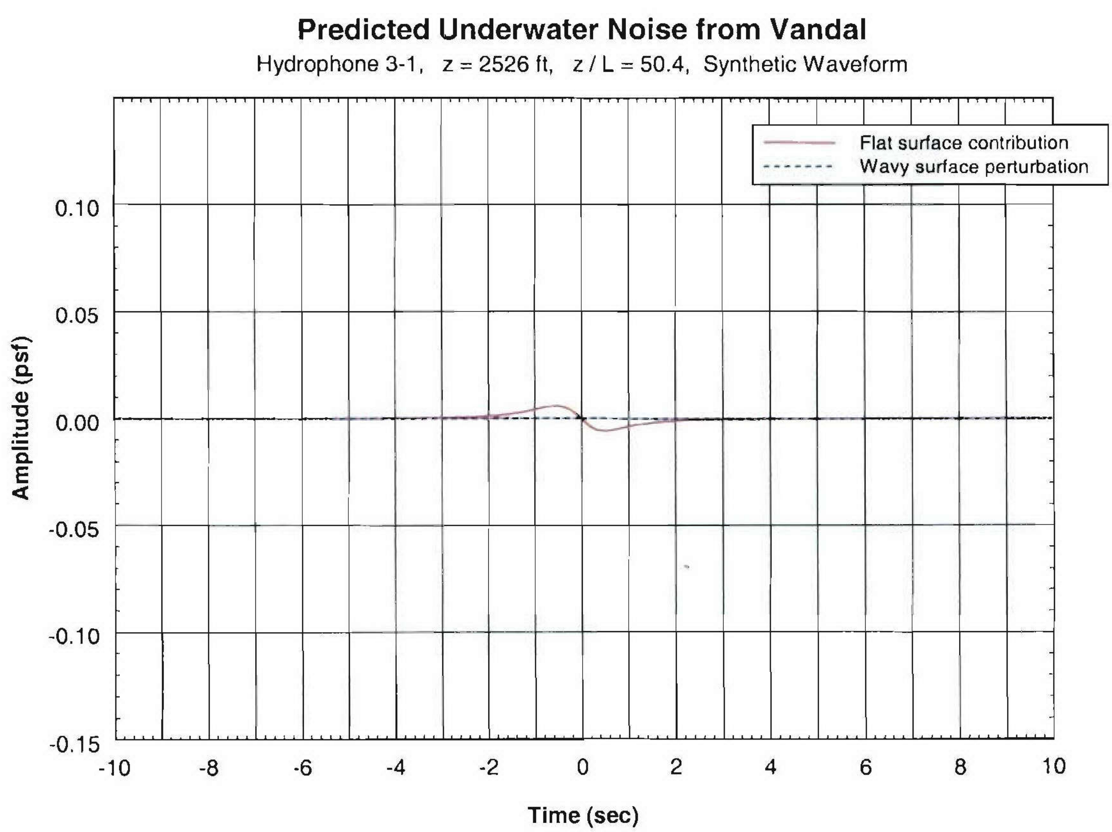

Figure 6. Predicted underwater noise at hydrophone 3-1 using synthetic waveform

Figure 6 shows that the signal obtained using the synthetic waveform (area-balanced, dipolar) is much smaller than that from the CFD waveform which has a non-zero monopole contribution. This is true even though the synthetic waveform's second moment (indicative of total energy flux) is 3.6 times greater than that of the CFD waveform (see Table 4.)

Using the synthetic waveform, the maximum predicted amplitude is 0.006 psf, whereas for the CFD waveform, the maximum was 0.12 psf (20 times higher.)

The wavy surface term is still of no importance, for the reason stated previously.

8 Computer execution time

In order to obtain 20 seconds of signal duration at this depth required 50,000 points in the complex 1-D transforms. Each case executes in roughly 2.5 hours. Computation of the complex perturbation potential at the surface required roughly 0.5 hours, and computation of the complex amplitude of the transformed solution required roughly 2 hours (per case.)

9 Conclusions

9.1 Comparing Figures 3 and 4 shows that the code described in Ref. 1 yields a predicted waveform which does not compare well with test data for the parameter set considered in this report. But this is inconclusive since the measurements were made at locations that were extremely far off track, in a region where the theory would predict virtually zero effect from the wavy surface.

9.2 Another limitation of these data is the lack of calibration. There is no way to deduce overpressure from the amplitudes shown in Figure 4. It is also unclear from Figure 4 how much of the signal is due to background acoustics (normal ambient noise) and how much is due to the Vandal overflight.

9.3 The predicted waveform at hydrophone 3-1 is a single positive pulse, with a duration of 5 to 8 seconds. Such a slow-rising disturbance would be indistinguishable from the passage of a normal gravity wave on the ocean surface, and would therefore be inaudible from the background of normal pressure variations due to such wave passages.

9.4 The cause of a predicted positive-only pulse at depth has been shown to stem from the non-zero first moment (monopole term) of the CFD-generated waveform. This monopole term increases (by a factor of 20) the maximum amplitude expected from an area-balanced waveform. (Compare Figures 3 and 6.)

9.5 If PMRF is to be used in the future for measuring underwater noise due to sonic boom, hydrophones should be calibrated and positioned directly below the flight path at depths not exceeding 200 feet. The flight path should be aligned with the water wave celevity vector as closely as possible. The hydrophones should respond well to frequencies from 3 to 2000 Hz. Without this additional instrumentation, the use of this range is marginal.

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